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ON A POSSIBLE FUNCTION OF DISRUPTIVE APPROACH IN THE FORMATION OF METEORITES, COMETS, AND NEBULÆ.[1] [2]

According to a familiar doctrine founded on the researches of Roche, Maxwell, and others, a small body passing within a certain distance (the Roche limit) of a larger dense body will be torn into fragments by differential attraction. In reality, the doctrine is applicable to the close approach of any two bodies of sufficient mass and density, but, as this more familiar case of a small body in close approach to a larger body is the one supposed to be involved in the origin of comets and certain meteorites, it will at first be taken as representative, and the wider application of the doctrine will be considered later.

The sphere defined by Roche's limit is computed on the basis of a liquid body whose cohesion is negligible, and whose self-gravitation alone is considered. It is obvious, therefore, that when cohesion is a notable factor, a small body might pass through the outermost part of this Roche sphere without suffering disruption, but that, if a nearer approach were made to the large body, fragmentation might take place. There is, therefore, a sphere within the Roche limit—which may be called the sphere of disruption—which is applicable to solid bodies as distinguished from liquid bodies.

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[1] I am greatly indebted to Dr. F. R. Moulton for suggestions and criticisms, and for formulæ for certain auxiliary computations that do not appear in the paper. I am under obligations to Mr. C. E. Siebenthal for the diagrams and other aid.

[2] From The Astrophysical Journal, Vol. XIV, No. 1, July 1901.

The size of this sphere of disruption compared with the Roche sphere depends, among other things, on the coefficient of cohesion and the size of the body to be disrupted. The coefficient of cohesion being the same, the sphere of disruption is relatively smallest when small bodies are to be disrupted, and becomes larger as the size of the body increases until it is sensibly as large as the Roche sphere. To illustrate this concretely, let disruption be supposed to take place along a diametrical section normal to the gravitative pull, dividing the body into halves. Let the bodies to be disrupted be spherical and homogeneous. The cohesion to be overcome will then obviously vary as the areas of the diametrical sections, and these areas vary as the squares of the radii of the bodies. But the masses of homogeneous spheres vary as the cubes of their radii, and the gravitative pull varies as the masses, modified by the differential tidal pull. It follows that mutual gravitation will more effectively disrupt large bodies than small ones. The limit at which the fragmentation of a solid body will take place will therefore approach more and more closely that of a fluid body as the size of the solid body becomes larger. For solid bodies of considerable dimensions, as asteroids, for example, the limit of disruption approaches sufficiently near Roche's limit to make the difference negligible in a general discussion. This will appear the more evident from the following numerical considerations.

Experimental data as to the tensile strength of rock are very limited, as the material is rarely used where tensile stresses are involved, but all the results of experimental tests given in Johnson's *Material of Construction* fall notably below 1000 pounds to the square inch, and this figure may be assumed as a liberal representative estimate. The weight of representative rock may be taken as $\frac{1}{10}$ pound per cubic inch. The tensile strength of an inch cube is therefore to its weight, at the surface of the earth, as 10,000 to 1. Using the same data, the tensile strength of a mile-cube of rock is to its weight as 1 to 6.36, while that of a 100-mile-cube is as 1 to 636. It will be seen, therefore, that in a comparatively small body the cohesive resistance to disruption bears a very small relation to the gravity of the mass, and that for large bodies it is negligible. For such bodies, the Roche limit may be taken as appreciably the limit of the sphere of disruption.

These numerical considerations, however, show that fragmentation by differential gravity acting alone will not become minute in any such case as that of a satellite or asteroid making a near approach to one of the planets.

But there are additional considerations that influence the practical result. The outer portion of the earth, and doubtless that of the satellites, asteroids, and cold planets generally, is deeply traversed by fissures—oblique and horizontal as well as vertical—which render it little more than a pavement of dissevered blocks which could be lifted away with little resistance beyond that of gravity. The relief of pressure upon the less fissured portion below, which would follow upon the removal of the overlying fissured portion, and the sudden exposure of this under portion to a lower temperature resultant from this removal, would develop new stresses; and these would doubtless give rise to additional fissuring and further easy removal, and thus the process would be extended. It is not improbable that the sudden rending open of a sphere that is hot within and the consequent exposure of the highly heated rocks in the interior to much lower temperatures would result in sufficiently great differential contraction to minutely disrupt the fragments irrespective of differential gravitation. The central portions of a body sufficiently hot to melt at surface pressures would doubtless pass immediately into the liquid condition on the removal of the pressure of the overlying rock, and this passage might, not unlikely, take on eruptive violence by reason of the included and highly compressed gases—or substances in a potentially gaseous state—in which case an extremely minute division would ensue. In the case of the earth, there is good reason to believe that if its interior gravitative stresses were suddenly removed, its internal elasticity would disrupt its exterior with much violence; and if the gravitative stresses were more gradually removed, the disruption would still be complete and pervasive, though less violent. How far a similar view may be entertained with reference to small bodies like the asteroids is uncertain, but even in these it is not improbable that the internal elastic factors would offset in some large part, if not entirely, the restraining force of the general cohesion of the mass.

From these considerations it would seem that the sphere of disruption, even in solid bodies of the nature of satellites and asteroids, may closely approximate to the theoretical Roche limit, while, for large bodies intensely compressed and very hot within, the practical sphere of disruption might actually exceed the Roche sphere. In the case of large gaseous bodies like the sun, intensely heated and compressed in the central portions, the disruptive or dispersive sphere must be much larger than the Roche sphere. But of this later. For the smaller solid bodies, and for present purposes, it may be assumed that the sphere of disruption is practically defined by Roche's limit.

The size of the sphere of disruption compared with the size of the body producing the disruption is an essential point in this discussion. The relative magnitude of these varies for every couplet of bodies brought under consideration, because it is dependent on density, cohesion, internal elasticity, and other varying factors. Roche has shown that, if the two bodies are incompressible fluids of the same density, and without cohesion, the limit of disruption is 2.44 times the radius of the body producing the disruption. The cross section of this body will therefore be to the cross section of the Roche sphere as 1 is to 5.95. The disk of the outer ring of *Saturn*, compared with that of the planet, whose density is unusually low, is a trifle below this ratio (1:5.29), but may be taken as a practical sanction of the figure theoretically deduced. The disk of the Earth, a dense body, is to the disk of the Roche limit, as computed by Darwin, as 1 to 7.5. It may therefore be concluded that where planets and planet-like bodies are concerned, the sphere of disruption has a cross section from 5 to 7.5 times as great as the central body It follows from this, that to a passing body the sphere of disruption exposes a disk five to seven times as great as the central body, and hence there are from four to six times as many chances that the passing body will invade the sphere of disruption without collision, as that it will strike the central body. In other words, *the fragmentation of a small body by near approach to a large one of the nature of the planets will be from four to six times as imminent as actual collision.*

That disruptions or explosions of some kind actually take place in the heavens, and that not uncommonly, seems to be implied by the sudden appearance of new stars, often with great brilliancy, followed by rapid decline to obscurity or extinction.[1] Five such new stars have been recorded during the last decade, and the survey of the heavens during this period has not been entirely exhaustive. The appearance of such new stars has been referred to collision, but their frequency has been felt to be an objection to this view, and other explanations, of the nature of eruptions or explosions, have been offered, but usually without assigning any probable cause for such extraordinary explosive action. The numerical objection is, in some measure, removed if the possibilities of disruptive approach be added to those of collision; and it will be seen further on that special conditions giving rise to distant approaches that are merely disturbing at the outset, may ultimately give rise to large possibilities for disruptive approaches.

That bodies pass within the disruptive sphere of other bodies is known from the fact that at least four comets have been observed to pass within the Roche limit of the sun, and these would quite certainly have been torn into fragments if they had not already been in that condition. There are, therefore, some observational grounds for the view that instances of bodies passing through the disruptive spheres of other bodies are not so rare as to render their results unimportant.

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[1] A fact which has become very familiar and impressive, since this was written, by the appearance of *Nova Persei.*

In the considerations now set forth, there seems to be warrant for the proposition *that solid bodies may suffer fragmentation without actual collision with other bodies, and that the bodies so disrupted may constitute comets so long as the fragments remain clustered, and that when these fragments become dispersed, they may constitute one variety of meteorites.* Only the first part of the proposition is novel—if indeed that is—for the disintegration of comets into meteorites is an accepted doctrine. The characteristics of comets other than their fragmental structure will need to be considered, but this may best be taken up later.

The foregoing conclusion, as a purely ideal proposition, does not appear to need discussion, unless the fundamental deductions of Roche, Maxwell, and others are questioned. Nor does its application to the adventitious cases of wandering bodies permit definite discussion, for neither the nature nor the number of such bodies is known; nor is the likelihood of their close approach to other bodies capable of estimation. But, on the probable supposition that the stars are centers of systems like our sun, there are hypothetical cases of approach of these systems to each other that by disturbance of the planetary orbits may lead on to disruptive approach of the individual bodies, and thus give effective application to the doctrine; and these invite consideration. It must be confessed that these cases, likewise, cannot be discussed with much satisfaction, since the movements of the assumed solar systems and their relations to each other are but very imperfectly known. Present data, however, warrant the assumption that the stars and their attendants are moving in various directions at various velocities, and that they are probably not controlled by any central body; nor do they probably follow concentric orbits so adjusted to each other as to forbid close approaches. The conception that the movements of the stars are somewhat analogous to those of the molecules of an exceedingly attenuated gas in an open space, actuated by the attraction of their common but dispersed mass, seems the most probable that can be entertained in the present state of knowledge. It may at least be made the basis for the assumptions necessary to further discuss the doctrine in hand.

Let two stars be assumed to be attended by secondaries like those of the sun, and to pass each other near enough to initiate serious disturbances in the orbits of the planets and satellites of the two systems. It is not necessary that this disturbance shall be so great as to bring about a disruptive approach of any of these bodies at once, but merely that this shall be the ulterior effect, which may be long delayed. The two systems need not necessarily invade each other's actual limit, that is, the two suns need not approach each other within the sum of the radii of the orbits of their outermost planets.[1] For example, in the ideal case of two solar systems, it is not necessary that the orbits of the two *Neptunes* shall actually cut each other. If the undisturbed orbits merely touch each other, or even closely approach each other, it seems clear that if *Neptune* be at the time coming toward the point of such ideal contact, or near approach, the attraction of the passing sun, together with *Neptune's* own momentum, will carry the planet far beyond the limit of its own ideal orbit into the sphere of dominant influence of the passing sun. At the same time, the paths of the inner orbits of both systems will be distorted in a quite irregular way, dependent on their various positions in their several orbits. The transfer of an outermost planet from one system to another under these conditions of general disturbance, or any other radical change in the orbits of the outer planets, will quite certainly lead on to other disturbances of orbit, some of which may sooner or later lead to disruptive approach, though the result of such a complication is beyond the reach of precise prediction.

A still more remote approach between two systems in which the only result is a pronounced elongation of the orbits of the two systems, may ultimately result in close approaches, for, if the orbit of any of the planets of the two systems be elongated so that its perihelion distance is less than the aphelion distance of the next inner planet, or its aphelion distance greater than the perihelion distance of the next outer planet, a disruptive approach, although it will not necessarily follow, because the planes may not coincide, and for other reasons, may result—if not at once, at least ultimately—as a consequence of the shiftings and modifications which such a disturbed condition involves. For example, it is obvious that by a favorable conjunction with a passing system whose sun is distant from *Neptune* considerably more than the radius of his orbit, there may be an elongation of the orbit of *Neptune* so as to make it cut one or more of the inner orbits, and that further modifications may arise out of these relations which will either increase or decrease the eccentricity. The principles applicable here are identical with those that have been found to produce radical modifications of the orbits of comets and that have been worked out by H. A. Newton and others.

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[1] In the illustrative examples it is assumed for convenience that the planes of the systems are normal to the systems' lines of movement.

To embrace the full possibilities of the case, it is therefore necessary to consider (1) the effects of systems passing each other at distances varying from those in which the outermost planets do not even cut each other's orbits, down to center-on-center collisions, and (2) to take account of the ulterior effects of disturbed orbits, as well as the immediate effects. This last is a consideration of no small importance in the qualitative as well as the quantitative application of the doctrine, for it distributes the effects over an indefinite period of time, and does not require their coincidence with the passage of the systems. The ulterior effects, so far as the disruption of secondaries is concerned, may apparently be much greater than the immediate effects. If this is not already clear, let a specific case be taken, as, for example, two solar systems passing each other so that their centers shall be 500,000,000 miles apart at nearest approach. If the planes of the systems are transverse to their paths, the ideal undisturbed orbits of the asteroids will touch, or closely approach, or slightly cut each other, as the individual case may be. The ideal orbits of the *Jupiters* will fall but little short of the passing sun, while the ideal orbits of *Saturn*, *Uranus*, and *Neptune* will fall outside the passing sun. While the precise results of such an event cannot be computed, it is quite certain that the secondary systems of the two suns will be most profoundly disturbed and the symmetrical and harmonious relations of the planetary orbits be utterly broken up. While even in this case the *immediate* contingency of a disruptive approach of one secondary to another may not be high, there will arise a *perpetuated series of contingencies*, the consequences of which will apparently be immeasurably greater than those immediately incident to the disturbing action, and the end of this perpetuated series of contingencies can scarcely be foreseen. Assuming that the great planets will exercise the same kind of influence over the small planets and asteroids that pass near them that *Jupiter* does over comets, the range of possible contingencies involves, on the one hand, closer and closer approaches and even collisions with the Sun and with other planets, and, on the other hand, the development of extremely elliptical orbits that will carry the small bodies into the sphere of influence of some other system. How large a proportion of these theoretical possibilities will be realized in a given disturbed system, it is impossible to determine, for the problem is far beyond the power of mathematical analysis, but it seems at least probable that results of moment may ensue.

If we may judge from the solar system, the small bodies may be assumed to be at least fifty times as numerous as the large ones, while not improbably they are a hundred or several hundred times as numerous. Other things being equal, they should show the characteristic effects of the action under discussion with correspondingly greater frequency. But the other conditions intensify these effects. A small body may be disrupted by a large one, but not necessarily the reverse. So, too, a small body may be thrown into an erratic orbit, while the orbit of the large body may not be sensibly affected, as shown by the changes in the orbits of comets caused by *Jupiter*. By far the most common effect of the close approach of two star systems should therefore be the fragmentation of the small bodies by being caused to pass within the spheres of disruption of the large bodies. As previously indicated, *the contingency of acquiring at the same time* *highly erratic orbits is imminent, and these are specially subject to still further changes, and thus these fragmental clusters come to possess by the very circumstances of their birth the second characteristic of comets, as well as the first.*

Whether they would possess at the same time, or come at length to possess, the *third* characteristic of comets, the attenuated matter of which cometic tails are made, is not so clear, since the nature of this matter and its condition are not yet fully known. The recent discoveries relative to the extreme ionization of matter and perhaps even its corpuscular dissociation, and the radio-activity of certain kinds of matter are at least very suggestive in this connection. Six of the elements reported by good authority as detected in meteorites, are known to possess, or to be habitually associated with, radio-active matter, viz., barium, bismuth, cerium, lead, titanium, and uranium. It is not very material here whether this radio-activity is really possessed by all these elements themselves, or simply by substances associated with them. If the coma and tails of comets are dependent on rare substances of a radio-active or extremely volatile nature, and hence permanently retensible only in the interior of bodies, it would be difficult to imagine conditions more favorable for setting them free in unusual volume than minute tidal disruption; particularly is this true if the retention of these substances is dependent on low temperature, as seems to be the case, since they are brought forth and driven away at a highly accelerated rate as the sun is approached. This view seems also to be supported by the fact that comets which remain long in the vicinity of the sun, as for example the short-period comets, lose their tails in a brief period.

If the attenuated cometic matter owes its essential peculiarities to electric states, these might perhaps be derivable from the revolutionary movements of the magnetic elements in the fragmental swarm, for by the hypothesis of tidal disruption the swarm should inherit a rotatory movement, and the fragments should contain both magnetic and magnetizable matter, variously associated with diamagnetic matter.

That short-period comets are subject to progressive disintegration, and that their scattered elements constitute one class of meteorites, is familiar doctrine. There seems no reason for withholding the conception from comets which have parabolic or hyperbolic orbits, for in certain cases such comets have shown signs of disruption and partial dispersion in their perihelion passages. To the dispersed elements of these comets of high velocity is assigned (in part at least) such meteorites as come to earth from diverse directions with velocities incompatible with an origin within the solar system.

It remains to consider whether the fragments derived from the disruption of an asteroid, satellite, or small planet through differential gravitative strain without collision, will satisfy the characteristics which meteorites display. Ample data for a judgment on this vital point will be found in the articles on the structure of meteorites in the first two numbers of the *Journal of Geology* for the current year, by Dr. Farrington, who, at my request, has kindly brought together in succinct and systematic form the essential characteristics of meteoric structure. A study of these characteristics will show that, while they embrace a great and very significant variety, they are all referable to the structures that are appropriate to small planets, while it is difficult to see how all of these characteristics can be found in derivatives from any of the alternative sources to which meteorites have been assigned, namely, volcanic action of the moon or of the planets, explosive projection from the sun, or individual aggregation in space. Some of the matter is fragmentary, implying surface conditions, while some of it is coarsely crystalline, implying deep-seated conditions. Some is volatile and combustible, implying the absence of high temperature throughout its whole antecedent history, while some as distinctly implies the presence of high temperature. In some meteorites the iron is segregated, while in others it is disseminated. Frequent brecciated structures imply fracturing and recementation. *Faulting and slickensides* demonstrate movements attributable to the parent body, but not to the meteorite itself. Veins imply internal transfer and redeposit of molecules. The absence of the oxidation of the iron accords with internal conditions, and also with the supposed absence of atmospheres from small planets, asteroids, and satellites. In short, every feature of the meteorites, save, of course, the external effects of fragmentation and of heating during their fall through the atmosphere, is assignable to small planetary bodies riven into fragments without great heat and, by reason of this, retaining the varied structure attained in the parent body.

As previously indicated, the disruption of a body like the earth, the main mass of which has a temperature much above the melting point of its substances at low pressures, and which is greatly compressed within by self-gravity, would doubtless cause it to burst forth into a luminous body with perhaps some dispersive violence. The progressive stages of distortion which take origin in simple tidal protuberances and grow to greater and greater degrees of deformation and crustal fissuring, until the final stage of disruption is reached, could scarcely fail to bring some parts of the ocean into contact with some parts of the heated interior, with inevitable Krakatoan consequences. Fragments of the crust under these conditions might possibly give origin to meteorites, but the probabilities of such fragments being projected beyond the 640,000 miles of the earth's dominant influence, or beyond the similar spheres of influence of other massive planets, would not seem to be great; and, if realized, the fragments would doubtless be reduced to dust, as in the case of the Krakatoan explosion, and this state of minute division would exclude such meteorites from recognition except as vanishing shooting stars. The probabilities are that the matter of a disrupted earth or a similar massive planet would be again assembled into a planetary body by its strong self-gravity. The phenomenon would therefore be that of a temporary star. Assuming considerable dispersion, it might be rather brilliant for a time, but would rapidly cool as the result of such dispersion, and soon sink into invisibility. In the case of such a body as *Jupiter*, accepting current doctrine as to his nature, the initial brilliancy must be much greater and the cooling to invisibility much more prolonged.[1] To phenomena of this class may perhaps be tentatively assigned certain of the temporary stars. Obviously these can only be such as had no prior visibility, and such as sink sooner or later again into invisibility. Whether this invisibility were due to the superficial cooling of the nucleus, or merely to a deep enshrouding of cooled vapor, would be immaterial.

It has already been indicated that a possible result of the serious disturbance of one solar system by the near transit of another would be a fall of some of the disturbed planets upon one of the suns. This also might be an ulterior rather than an immediate result, through the modifying effects of other planets, as well as the direct effects of the primary disturbance. Such a fall must be presumed to give rise to a notable increase of heat in the central body, as well as to mechanical effects, both of which would be conditioned by the mass and velocity of the secondary. An outburst of greater or less brilliancy must be presumed to be the result. The mechanical effects upon the sun would probably involve great changes in temporary density and condition, as well as outshoots of hot gases in various directions at high velocities. The effects might thus coincide with the phenomena of that class of the temporary stars in which a luminous state precedes and follows the outburst, and in which varying densities or high velocities in opposite directions seem to attend the temporary brilliant stage.

The disruption of suns has been neglected thus far. While, under the terms of the hypothesis, the disruption of these bodies must be rarer events than the fragmentation of the more numerous small bodies, the results must be correspondingly more important, by reason of their magnitude and character.

It has already been observed, in passing, that the internal elasticity of large hot bodies under great self-gravitative compression may so far aid in disruption, by coöperation with the differential gravity of an adjacent body, as to cause dispersion even before the Roche limit is reached. In the case of very large bodies that are already gaseous, such as the sun, this phenomenon gives rise to a special case of extreme interest. Under this special case, there arise a large variety of particular instances due to the varying sizes, velocities, paths, rotations, and constitutions of the couplets of stars concerned, and also to the adventitious effects of their secondaries; but, for a simple illustrative case, let it be assumed that two bodies of equal masses and equal velocities are approaching each other on parabolic paths, and that at periastron they will pass through each other's spheres of disruption, or rather, spheres of dispersion. For convenience, let if be assumed that one of these bodies (*A*, Fig. 1) is gaseous, while the other (*B*) has already become so cold and solid as to act essentially as a unit, though disrupted. The history of the dispersion of the gaseous body may then be followed alone. Let the rate of rotation of the gaseous body (*A*) be relatively low, as in the case of our sun. It may then be neglected in a general discussion, since as a dynamic factor it is trivial compared with the enormous energies of momentum and of elastic dispersion involved. This will appear clear in the outcome. Furthermore, the direction of rotation with reference to the parabolic paths might happen to be any one of an indefinite number, in many of which the effect would be inconsequential, even if the energy were large. In the close approach of these two bodies the two great dynamic factors of special interest are (1) the tidal distortion, and (2) the elastic expansion of the gaseous body.

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[1] Such a body as *Jupiter* might perhaps, under proper conditions, be dispersed in the same manner as a sun as sketched beyond.

While the two bodies are yet distant from each other, they must begin to take on elongation of the tidal type as the result of their mutual differential attraction, this elongation being aided by the high internal mobility and elasticity of the gaseous body. As the bodies approach periastron, this elongation must progress at an accelerated rate. At the moment of the entrance of the gaseous body *A* upon the Roche sphere of the body *B*, self-gravitation, in accordance with Roche's doctrine, will have been completely neutralized on the lines joining the centers of *A* and *B*, and its restraining influence upon the elasticity of the gaseous body on these lines will have been removed, while the gravitative constraint in the transverse section will be increased. The expansive energy of the compressed gaseous matter will therefore be left to exert its full projectile force in the direction of the axis of elongation. While I am unable to offer a numerical estimate of the magnitude of this expansional energy in such a body as the sun, it is certainly of a high order of magnitude. The speed at which prominences are projected from the sun under present conditions closely approximates to the parabolic velocity with respect to the sun, and this is accomplished in spite of gravitation and a resisting atmosphere.

The case in hand, therefore, starts with simple tidal elongation at a distance, and increases to an explosive maximum as the bodies approach periastron. This increase is at first gradual, but in the last stages of approach to periastron the acceleration is exceedingly rapid. In any attempt to follow the process in more detail, adhering to the recognized principles of tidal action, four particulars are of special moment: (1) the progressive elongation of the body, (2) the change in the direction of tidal distortion, (3) the lag of the line of maximum elongation behind the line of maximum attraction, and (4) the rotatory effects arising from the gravitation of *B* on the tidal protuberances of *A*, which in this case will be peculiarly effective because of the enormous distortion of *A* and the very close proximity of *B* at the critical stages. The principles from which these effects arise are thoroughly demonstrated and are familiar to all students of tidal phenomena, and it is only their special applications to this case that need be discussed. The rotatory effects are a little peculiar in that both of the tidally acting bodies are rapidly approaching each other, and developing extraordinarily powerful differential attractions, while at the same time they are swinging about their common center of gravity. Near periastron they may be regarded as performing a semi-revolution about each other. By the terms of the special case in hand, this semi-revolution must be performed in a very few hours. During these few hours the gaseous body (*A*) is undergoing elongation at a rate not much less than that represented by its full explosive competency. The rotational forces are diagrammatically illustrated in Fig. 1, in which the lag is merely estimated and the distortion of *A* is simplified while that of *B* is neglected.

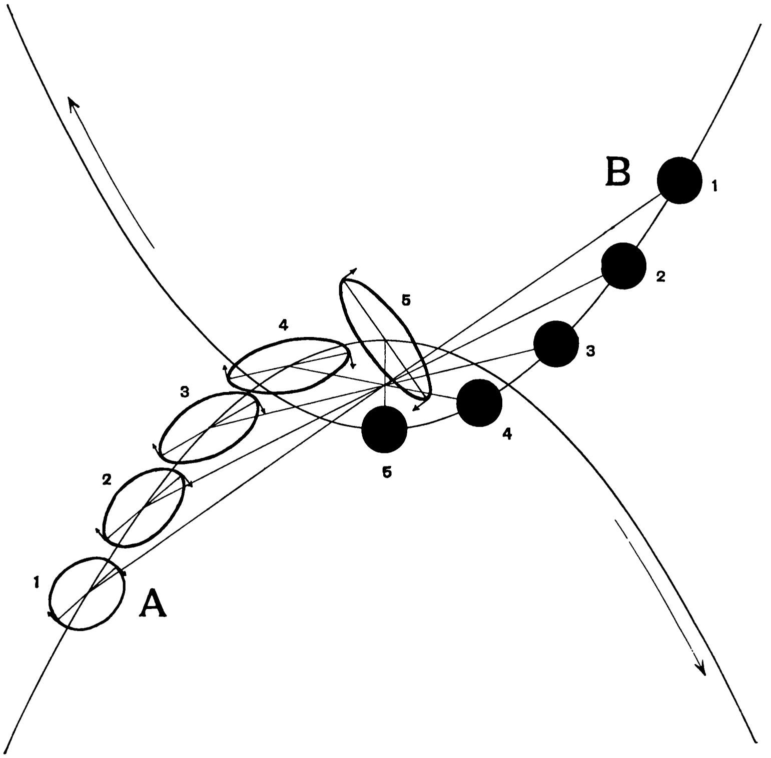


FIG. 1.—Diagram illustrating the elongating and rotatory effects of a solid stellar body, *B*, upon a gaseous sun, *A*, during their mutual approach to periastron. $A^{1, 2, 3, 4, \& 5}$ indicate successive positions, changes of form, and rotation of the gaseous star on its approach to periastron. $B^{1, 2, 3, 4, \& 5}$ represent the successive positions of a solid body of equal mass and velocity which is assumed for convenience to remain intact. Position A^1 corresponds to B^1, A^2 to B^2, etc. The lines joining their centers indicate the successive directions of mutual attraction. The arrows indicate direction of movement.

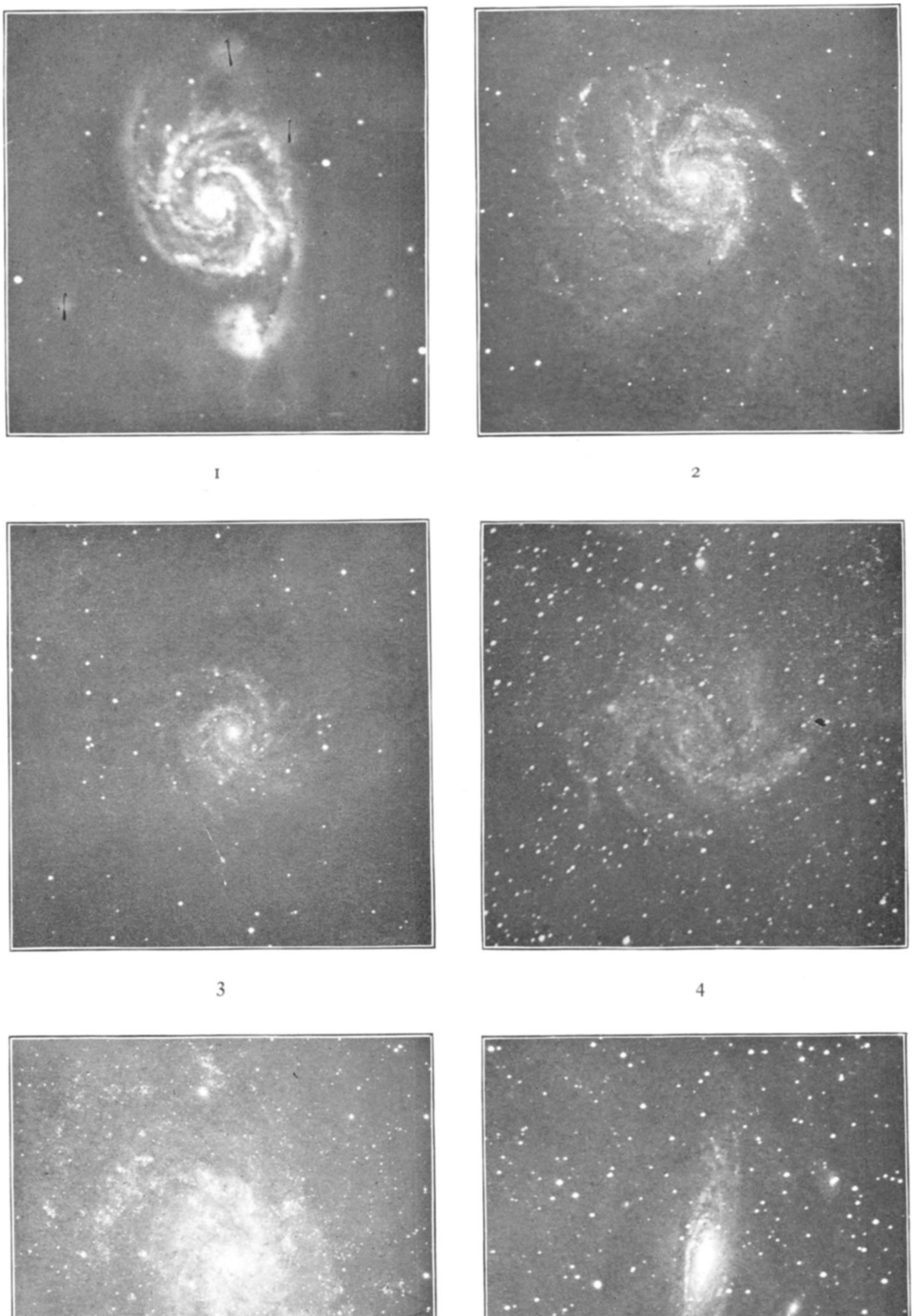
It is assumed that the lag of the axis of elongation of *A* is uch that the effective path of explosive projection will be directed to the rear of *B*. It must be noticed that if the center of *A* passes through the outer part of the Roche sphere of *B*, the nearest edge of *A*, if undistorted, would pass within two or three hundred thousand miles of *B*, and hence that the projective elongation of *A* must pass critically near *B;* but the relative speed of the bodies *A* and *B* is so great—both being near the parabolic velocity with respect to the other—that the projected matter of *A* can only collide with *B* on the supposition that the velocity of projection at least equals the parabolic velocity of the body and acts instantaneously, the last of which is impossible. This is based on the assumption that the transverse component of the attraction of *B* prevents the elongation of the minor axis of *A*, which is true of liquid bodies tidally affected, but might perhaps break down in a gaseous body under these extraordinary conditions. The point, however, is not important here, for if the edge of the projected part of *A* collide with *B*, it will only intensify the rotatory effects under consideration, and such collision is contemplated as an essential feature of the next following case, but is excluded here as the effects of *approach without collision* is the special theme under discussion.

The very close approach of the elongated extremity of *A* to *B* obviously gives great effectiveness to the rotatory influence of *B*'s attraction upon it. If the amount of this attraction be represented by the fall of $\frac{1}{1000}$ part of the mass of *A* toward *B* at a mean distance of 200,000 miles from *B*'s surface—the masses of *A* and *B* being each equal to that of the sun—such a fall for about two hours and a half would generate a momentum equal to the whole revolutionary and rotatory momentum of the present solar system. It would appear, therefore, that under the conditions postulated a rotation of a highly effective kind must be imparted to the elongated body. It will now appear that the previous rotatory energy of the sun, which is only about 2 per cent. that of the solar system, is a negligible factor.

The history of *A* then takes this form: (1) A very rapid elongation in the hour or two preceding its entrance upon the Roche sphere. (2) After entrance upon the Roche sphere, an explosive elongation actuated by the elastic energy then remaining in the body unrestrained by self-gravity in the axis of elongation. (A portion of the original elastic energy had been consumed in the previous elongation and a corresponding amount of momentum had been acquired, the larger component of which would be effective along the changed line of elongation.) (3) After passing out of the Roche sphere, the restraints of gravity begin again to be felt and rapidly increase as *A* and *B* retire from each other, but the distance to which the extremities of *A* have already been projected, and the new relations thereby assumed to the remaining mass of *A*, and to *B*, render the renewed gravitative influence far less effective than the original. and the projection must continue until the momentum acquired is overcome. (4) Coincident with this projection a constantly increasing rotation toward *B* has been generated, which possibly reached an effectiveness comparable to that of the solar system. *The effects of explosive projection combined with concurrent rotation must obviously give rise to a spiral form.*

It seems clear from the nature of the case that there would be a certain brief period when the climax of projective effects would be reached, and that a stream of material of much greater mass and velocity than at other instants would at this time be projected from the extremities of the elongated mass in both directions. There should therefore be two chief arms to the resulting spiral starting from the opposite points of the central mass and extending outward to the limits of the spiral—indeed constituting the most outlying portions of the spiral. These must be curved in a common direction by the rotation of the mass. Such predominant arms are notable features in the typical spiral nebulæ. They are well shown in Nos. 1, 2, 3, 4, 5, and 6, Plate I, all of which are reproductions from photographs furnished by the late Professor Keeler.

In the illustrative case that has just been discussed the solid body *B* was made to represent a convenient possible case but



SPIRAL NEBULAE

1. *M 51 Can. Ven.=G. C. 3572–3574*
2. *M 101 Urs. Maj.=G. C. 3770–3771*
3. *M 74 Piscium=G. C. 372*
4. *H IV 76 Cephei=G. C. 4594*
5. *H 33 Trianguli=G. C. 352*
6. *H I 53 Pegasi* and her nebula

one whose real frequency is quite unknown, since extinct suns are beyond the reach of observation. If the active lives of suns are no greater than the periods deduced from computations founded on the Helmholtz theory of solar heat, extinct suns should either be numerous, or the whole previous history of the stellar system must have been short; or else, as a *tertium quid*, some effective means of regeneration must be assumed.

In the more typical case of two live suns coming into such close relations, its seems probable that mutual dispersion might follow without serious collision, since the analysis of the phenomena seems to show that the mutual elongations of the live suns would develop on essentially parallel lines whose constant shiftings would be mutually consonant, as illustrated in Fig. 2. If no serious contacts were developed, the two resulting spirals would separate and pursue the paths normal to their parent stars, with such modifications as may have resulted from the loss of energy involved in giving rotation to the nebulæ.

If, however, the periastron approach is so close that partial collision ensues, the analysis seems to indicate that the elongated bodies which would be developed previous to contact would not collide end to end centrally, but by a lateral shear, as illustrated in Fig. 3. In this case the arrested momentum combines with mutual attraction to give a rotatory movement of the highest order, and the heat and the resilience from impact must combine to intensify the dispersive competency. The arrest of momentum may be presumed to go so far in some cases as to cause the two bodies to unite to form a single spiral nebula of the largest and most dispersed order, such perhaps as the well-known great spiral nebulæ; or the arrest may be partial, and certain parts of one or the other, or both, of the masses may escape. In No. 1, Plate I, we seem to have a possible example of this, in which the escaping, or partially escaping, mass[1] is still associated with the longest arm of the spiral.

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[1] This is assumed to have been a dead sun because of the limited evidence of explosive action.

In case the collision of two suns becomes essentially central, a general dispersion of the most violent sort may be inferred to follow, and this may find exemplification in the vast irregular nebulæ, which are in many cases more or less radiant, and in some cases consist of two irregular masses which perhaps represent the wrecked originals. The collision of dead suns in which disruption shortly preceded actual impact may also play a part in forming irregular nebulæ.

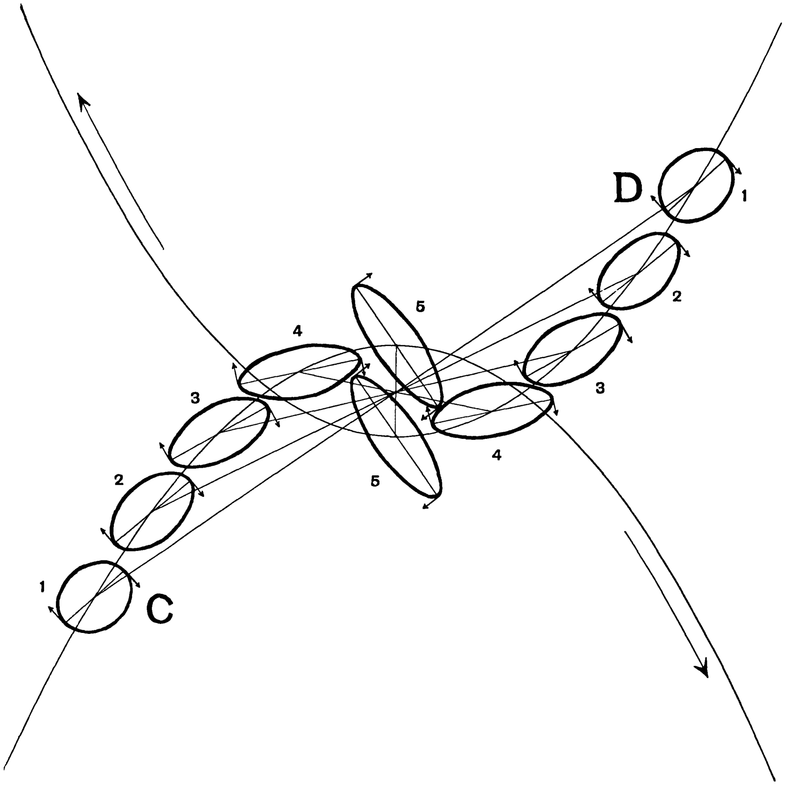

FIG. 2.—Diagram illustrating the progressive elongation and rotation of two suns, *C* and *D*, approaching perihelion. The position C^1 corresponds to D^1, C^2 to D^2, etc.; the lines joining these indicate the successive directions of mutual gravitation, and the arrows indicate direction of movement. The progressive elongation, the lag, and the rotation of the bodies at successive stages are diagrammatically indicated.

Speculation may perhaps go so far as to attribute ring nebulæ to the central penetration of a concentrated solid body through a gaseous mass.

It is as impossible as it is unnecessary to consider here the infinite variety of sub-cases which the hypothesis under consideration involves, but it seems advisable to note that the case of equal suns with equal velocities, which has been used in illustration, is not the most prevalent case; for inequality of mass and momentum is quite certainly the rule, rather than equality or sub-equality. Where one of the suns is much smaller than the other, the dispersive influence will be most largely felt by it,

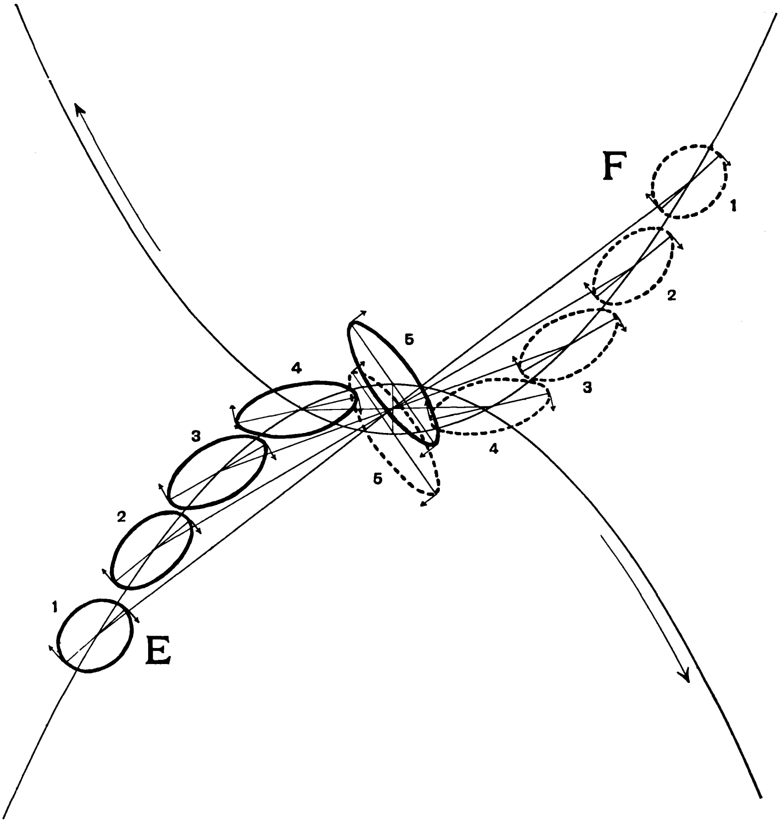

FIG. 3.—Diagram illustrating the same phenomena as Fig. 2, save that the periastron distance is so small that the bodies collide by a shearing stroke.

and so it seems probable that there may be a series of cases in which the minor members of the couplets are dispersed with different intensities into complete nebulæ while the major members only suffer varying degrees of eruptive action or partial conversion into nebulæ and so perhaps become stars with nebulous adjuncts or atmospheres. Under this conception small nebulæ should be much more numerous than large ones. If large hot planets, such as Jupiter is supposed to be, are potentially gaseous, and if by disturbing approaches of stellar systems such planets are thrown out of their allegiance to their primary suns and take on comet-like courses, they would be specially liable to disruption and dispersion into small nebulæ, and would augment the number of the latter.

Whether the existing stellar movements and the mutual attractions of the stars are such as to give any substantial ground for believing that close approach can be a *chief* agency in producing comets, meteorites, and nebulæ, can only be determined when some approximate knowledge of the dispersion, the masses, the velocities, and the paths of the stars is gained. If the stars be considered simply as so many scattered bodies flying through space in straight lines at computed rates, and all mutual attractions and systematic relations be ignored, the frequency of disturbing approaches would not seem to be great and the quantitative value of the doctrine here sketched would seem to be questionable. The solar system has certainly never been subjected to disturbing approach since its present organization. But the assumptions made are certainly not the true ones and may not be representative. Besides the mere hazard of flying bodies, the mutual attraction of two stars after they enter upon each other's spheres of dominant influence — and these are very large — increases notably the probabilities of a disturbing approach even in the case of stars moving in opposed directions, while in the case of stars moving in sub-parallel and gently converging paths at sub-equal velocities, it may apparently become a dominant factor. At the average computed distances of the stars from each other, their mutual attractions are very slight, and in the central portion of the stellar system, in which the sun seems to be placed at present, the general attractions are probably nearly balanced. Two stars, therefore, whose speeds are sub-equal and whose paths gently converge, may be controlled almost freely by their mutual attractions after they come within the spheres of each other's dominant influence. Such stars under mutual control would describe paths relative to each other similar to those assumed in the discussion. Their closeness of approach at periastron would be determined by the *relative differences* (not the total amounts) of their speeds and momenta. The principle of sub-parallel movements applies here and gives results quite at variance with those that obtain in cases of opposed movements, where the *relative sums* of the velocities and momenta are to be considered. The movements of the long-orbit comets seem to be concrete expressions of this principle, as their perihelia are largely clustered on the front side of the Sun, *i. e.*, the side toward which it is moving, and they make close approaches to it. Such star clusters as the *Pleiades*, the members of which seem to have proper movements nearly the same in amount and direction, are doubtless also expressions of the principle of sub-parallelism, and in their remarkable nebulosity they may at the same time illustrate the doctrine of disturbed secondaries leading on to dispersive action, a part of the product of which remains associated with the stars themselves, while a part is more or less widely scattered, as the terms of the doctrine require.

If our stellar system has a definite boundary and is a flattened spheroidal cluster or a discoid, and if the ideal paths of the stars are elongate orbits stretching from border to border across the heart of the cluster (except as diverted by close approaches), then the orbital speeds and momenta should be lowest on the outer surface, and the paths should there be most frequently sub-parallel, and hence the conditions for the close approach of two suns through their reciprocal attraction be there most favorable. Now, visible nebulæ are most frequent in the regions polar to the Milky Way, and they may be regarded as lying on the flat sides or outer border of the stellar discoid where these conditions of low orbital velocity and momenta and prevalent sub-parallelism are dominant, and thus the distribution of nebulæ and the doctrine of close approach seem to be, so far at least, brought into harmony.

It may be needless to remark that the general conception lying back of the doctrine of dispersion by close approach has a complementary regenerative or reconstructive phase, which, taken with the dispersive phase, makes up a cyclic process. With the disruptive action there is correlated a reciprocal concentrative action, which is supposed to reproduce organized systems out of the wreckage of disrupted systems. The notion is further entertained that the two processes may be mutually self-adjustable, within the limits of general conditions, and thus may give a large degree of perpetuity to the existing phase of the stellar system.

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